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(54) **SYSTEM AND METHOD FOR AUTOMATED SURFACE ANOMALY DETECTION**

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B64F 5/10	(2017.01)

(Continued)

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CPC ***B64F 5/60*** (2017.01); ***B64F 5/10*** (2017.01); ***G06T 7/0004*** (2013.01); ***G06T 17/10*** (2013.01); ***G06V 20/50*** (2022.01)

(58) **Field of Classification Search**
CPC G06T 7/0004; G06T 17/30; G06T 7/0002; G06T 17/10; G06T 19/20; G06T 17/205;
(Continued)

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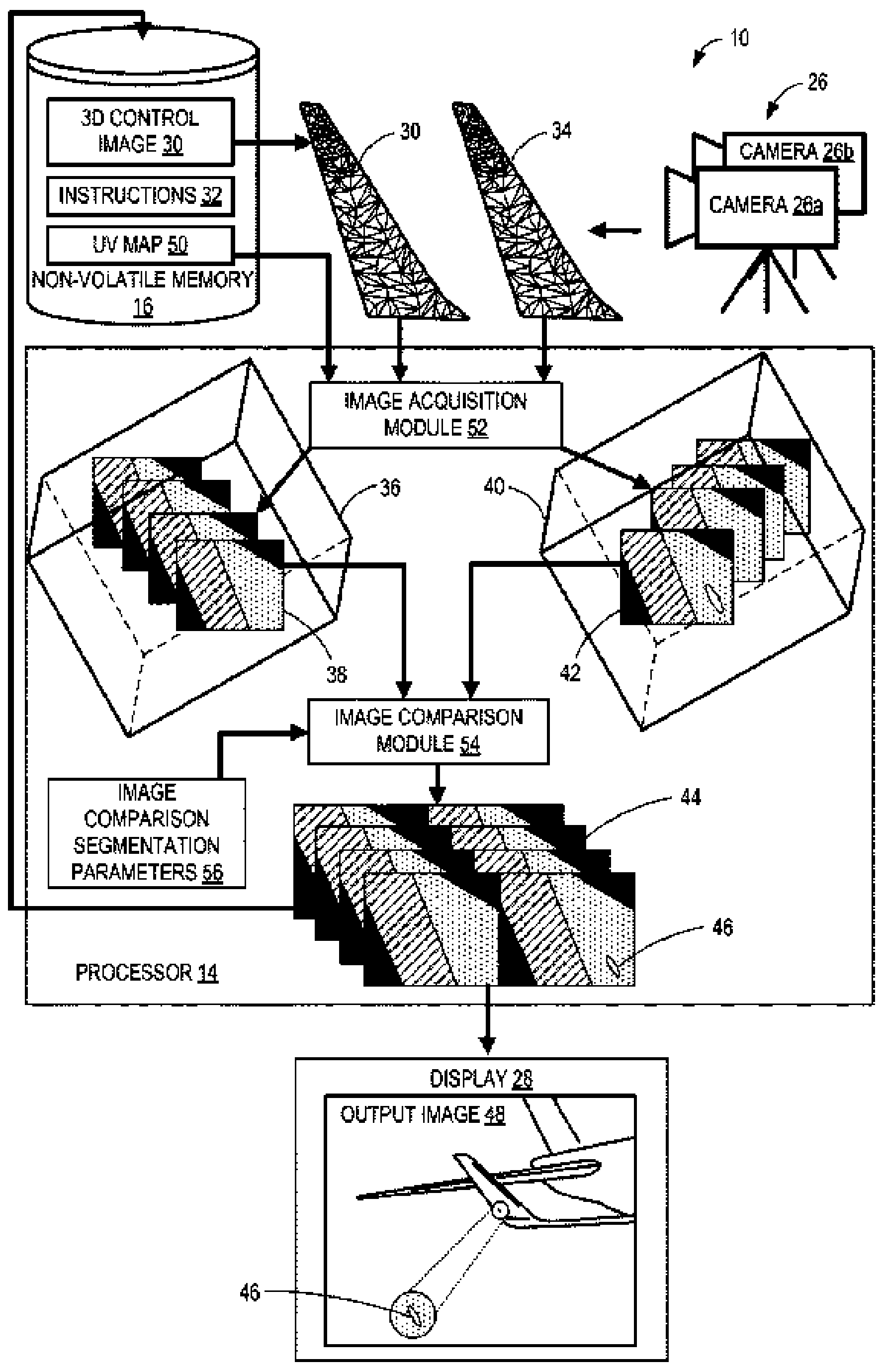
(57) **ABSTRACT**

A system for automated surface anomaly detection includes at least one processor which is configured to retrieve from non-volatile memory a 3D control image; capture a 3D target image depicting at least the portion of the exterior of a target object; generate 2D target planar images of the target object based on the 3D target image, using a first plurality of virtual cameras; generate 2D control planar images of the control object based on the 3D control image using a second plurality of virtual cameras, the 2D control planar images corresponding to the 2D target planar images of the target object; detect at least one difference between the 2D target planar images and the 2D control planar images; and generate and cause to be displayed an output image comprising a depiction of the target object with the at least one difference indicated.

20 Claims, 10 Drawing Sheets



(51) **Int. Cl.**

B64F 5/60	(2017.01)
G06T 7/00	(2017.01)
G06T 17/10	(2006.01)
G06V 20/50	(2022.01)

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CPC ... G06T 2200/04; G06T 15/08; G06T 15/205; G06T 17/00; G06T 11/00; G06T 11/003; G01N 21/8851; B25J 9/1674; B25J 9/1697; G05B 19/41875; G06V 20/50; G06V 20/64; B64F 5/10; B64F 5/60; G06N 20/00; G06N 3/02; G06N 3/08

See application file for complete search history.

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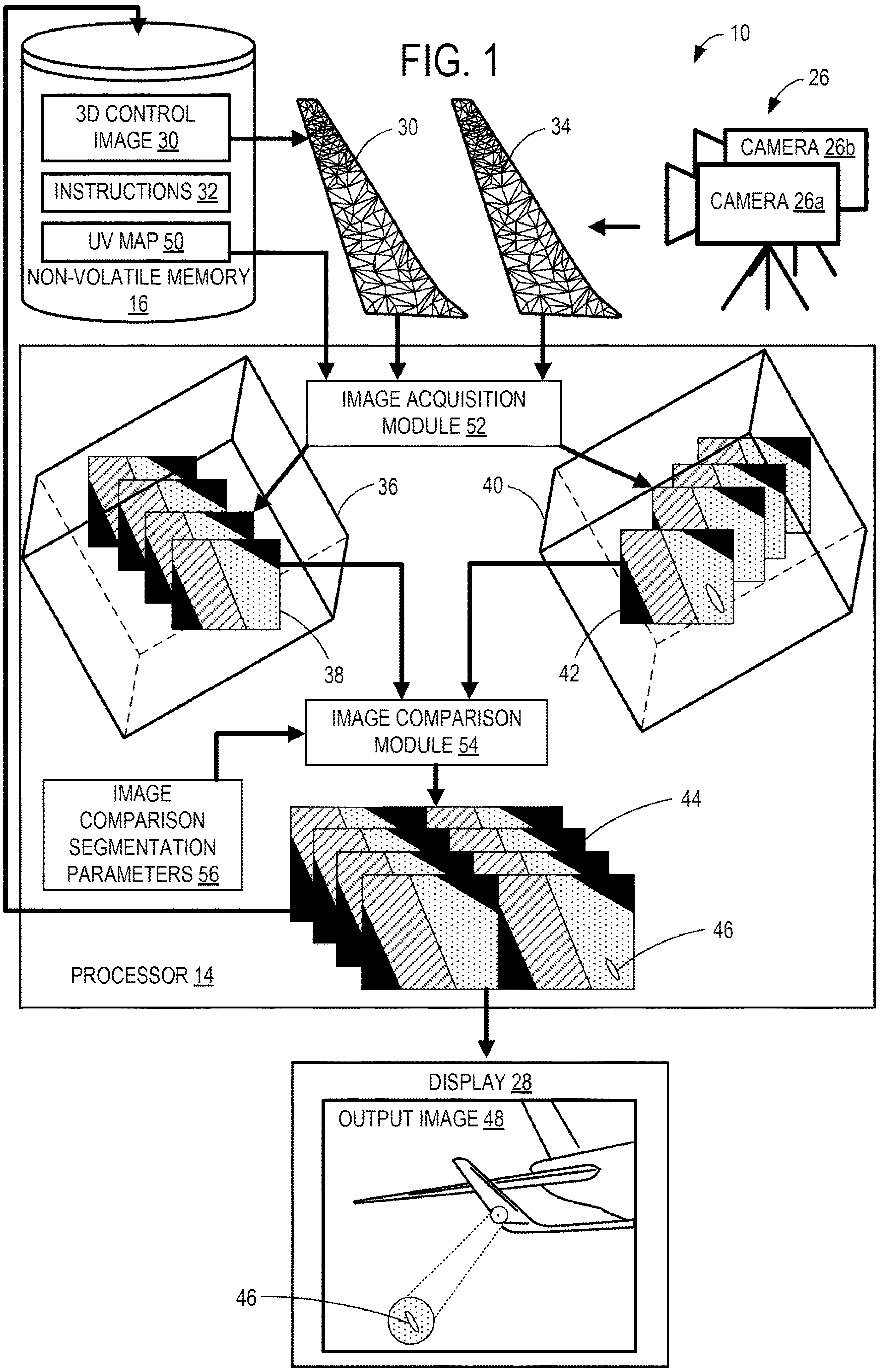
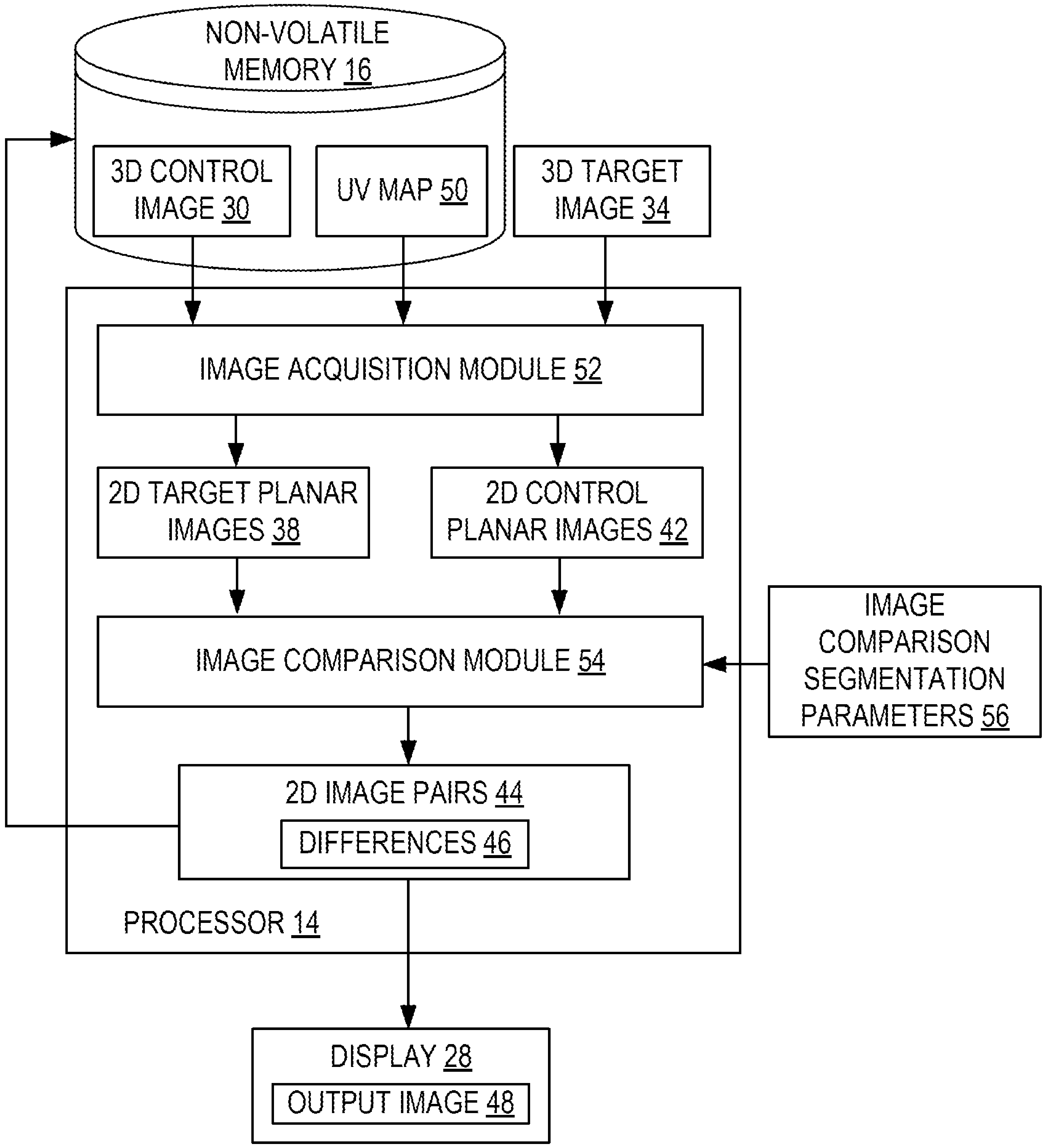
FIG. 1


10
26
CAMERA 26b
CAMERA 26a
3D CONTROL IMAGE 30
INSTRUCTIONS 32
UV MAP 50
NON-VOLATILE MEMORY 16
30
34
IMAGE ACQUISITION MODULE 52
36
40
38
42
IMAGE COMPARISON MODULE 54
IMAGE COMPARISON SEGMENTATION PARAMETERS 56
44
46
PROCESSOR 14
DISPLAY 28
OUTPUT IMAGE 48
46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3D CONTROL IMAGE 30
UV MAP 50
3D TARGET IMAGE 34
IMAGE ACQUISITION MODULE 52
2D TARGET PLANAR IMAGES 38
2D CONTROL PLANAR IMAGES 42
IMAGE COMPARISON MODULE 54
IMAGE COMPARISON SEGMENTATION PARAMETERS 56
2D IMAGE PAIRS 44
DIFFERENCES 46
PROCESSOR 14
DISPLAY 28
OUTPUT IMAGE 48

FIG. 2

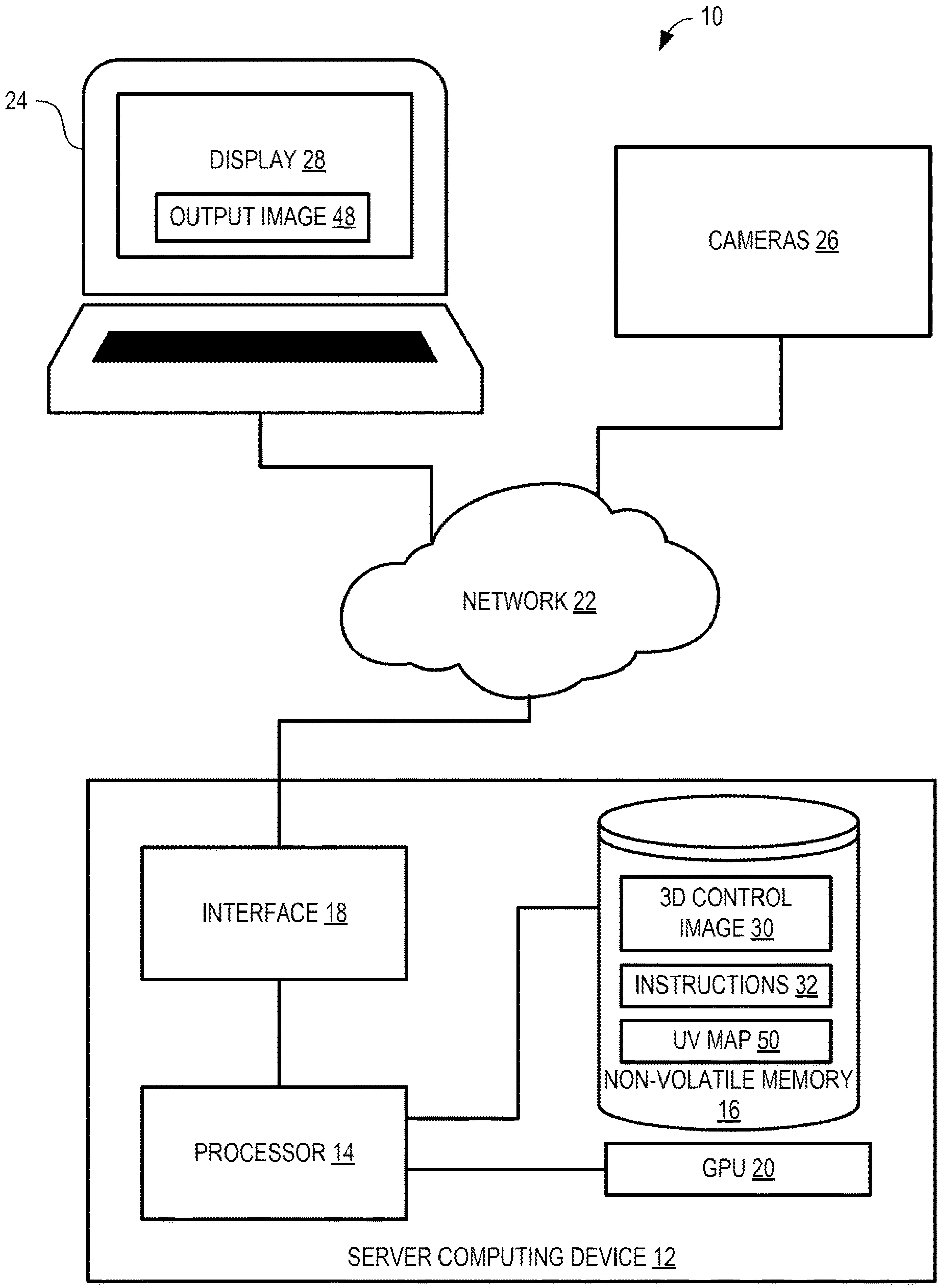
10
24
DISPLAY 28
OUTPUT IMAGE 48
CAMERAS 26
NETWORK 22
INTERFACE 18
3D CONTROL IMAGE 30
INSTRUCTIONS 32
UV MAP 50
NON-VOLATILE MEMORY 16
PROCESSOR 14
GPU 20
SERVER COMPUTING DEVICE 12

FIG. 3

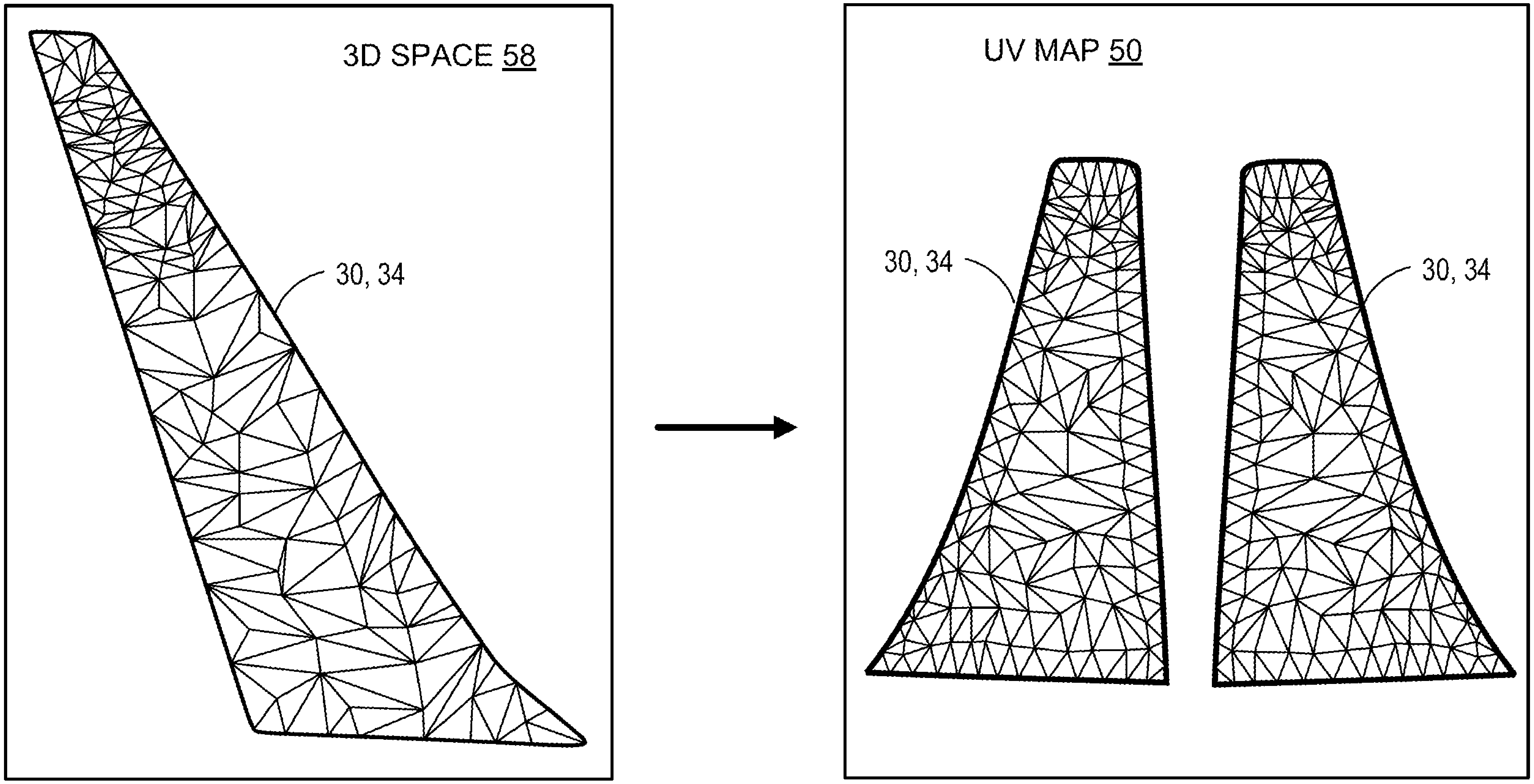

FIG. 4

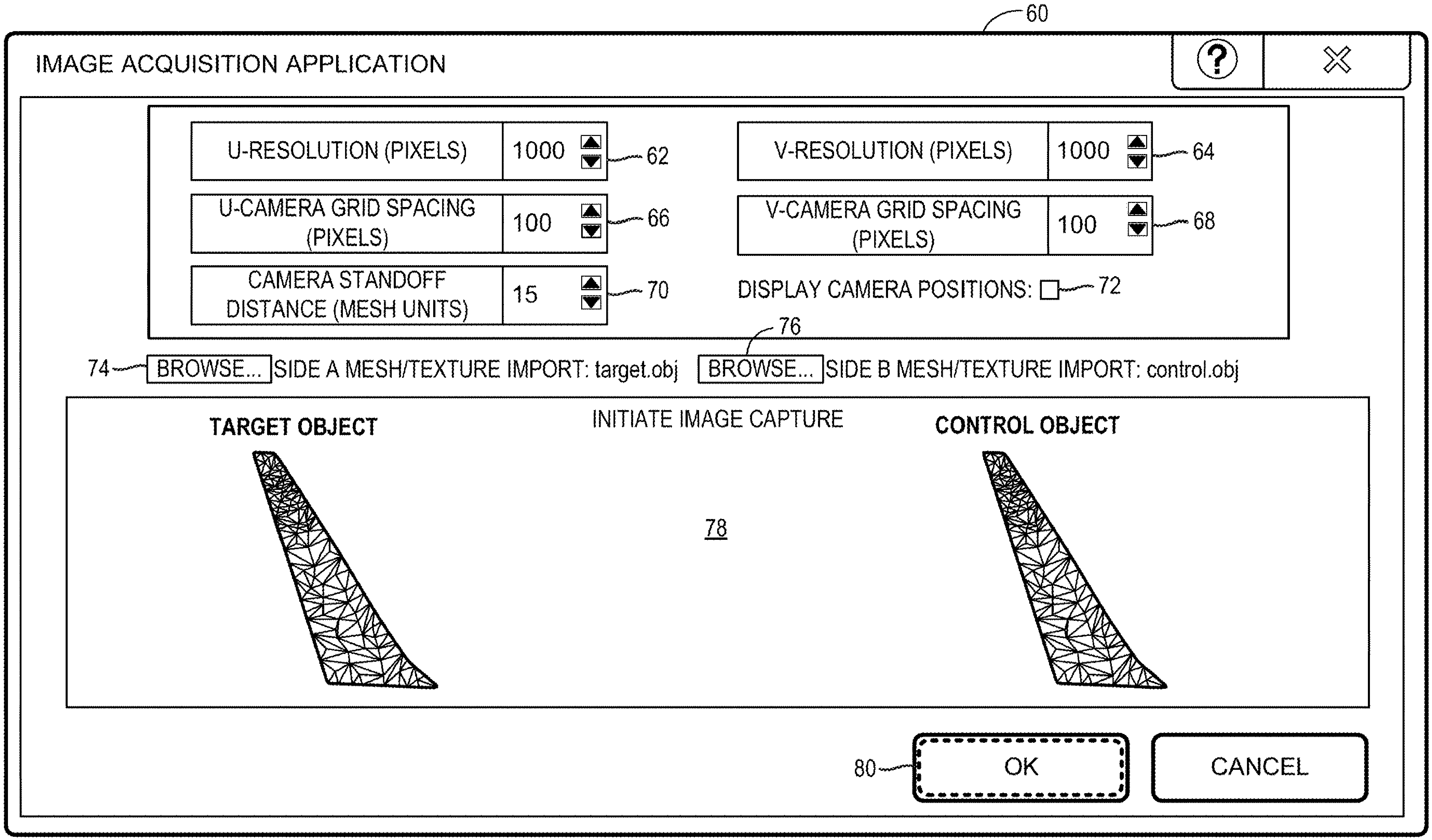

IMAGE ACQUISITION APPLICATION

U-RESOLUTION (PIXELS) 1000

V-RESOLUTION (PIXELS) 1000

U-CAMERA GRID SPACING (PIXELS) 100

V-CAMERA GRID SPACING (PIXELS) 100

CAMERA STANDOFF DISTANCE (MESH UNITS) 15

DISPLAY CAMERA POSITIONS: ☐

SIDE A MESH/TEXTURE IMPORT: target.obj

SIDE B MESH/TEXTURE IMPORT: control.obj

FIG. 5

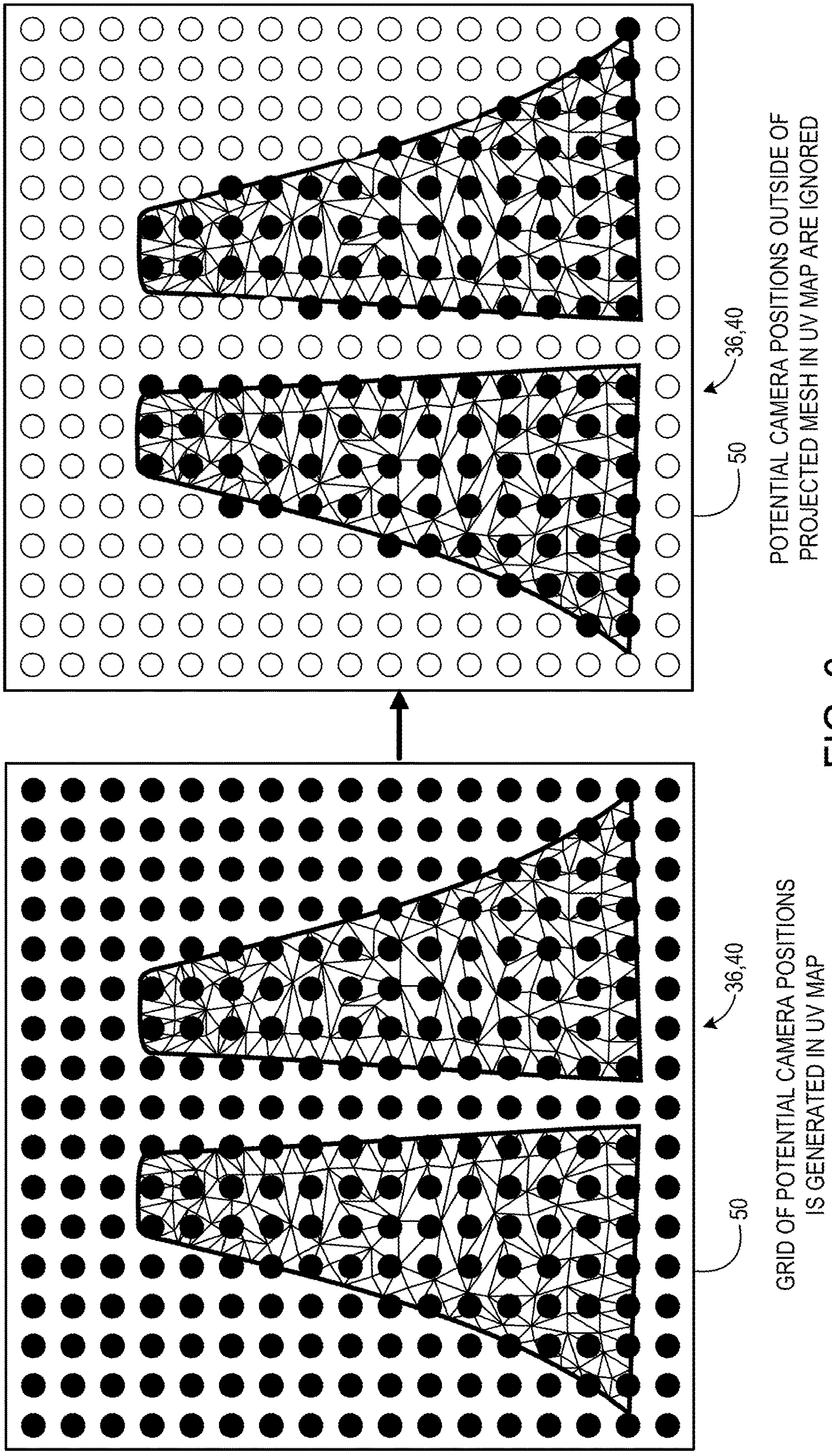
GRID OF POTENTIAL CAMERA POSITIONS IS GENERATED IN UV MAP
POTENTIAL CAMERA POSITIONS OUTSIDE OF PROJECTED MESH IN UV MAP ARE IGNORED
36,40
50
36,40
50

FIG. 6

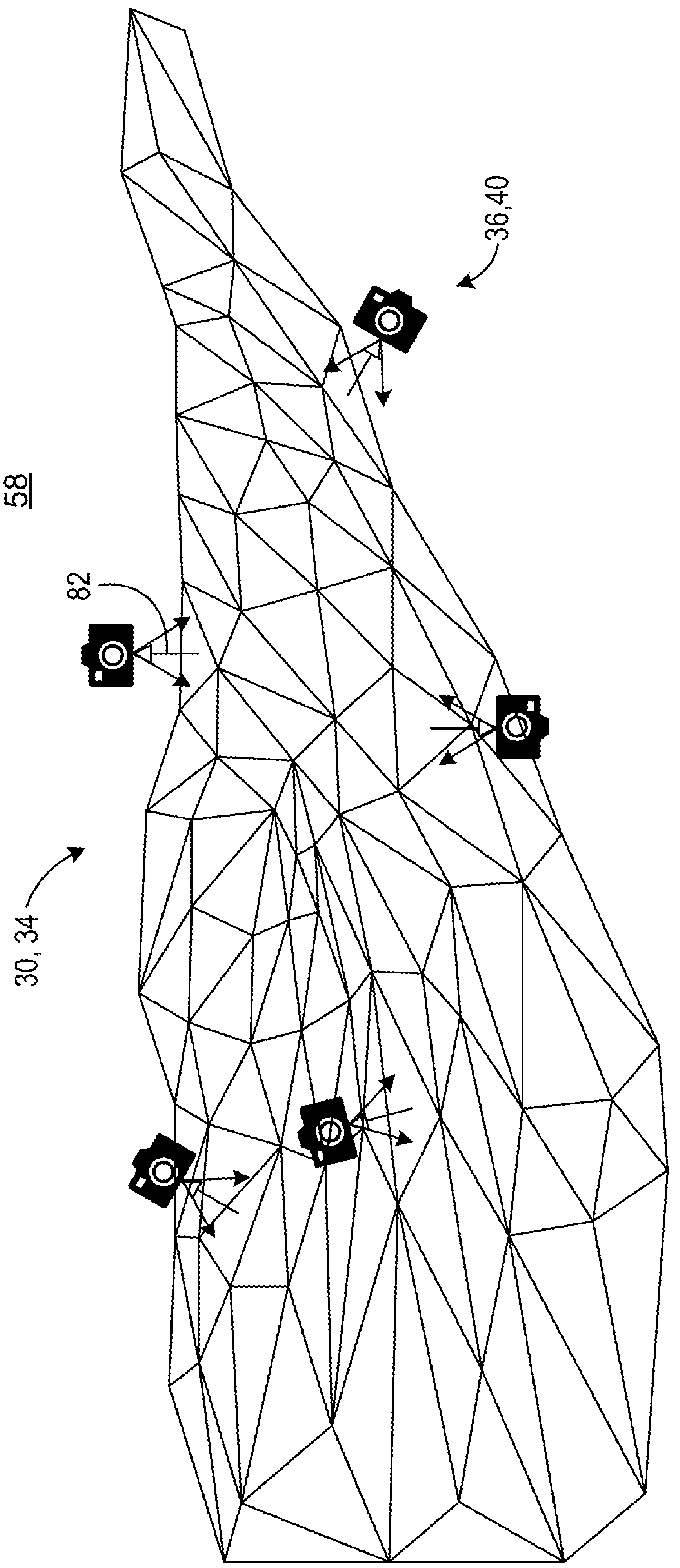

FIG. 7

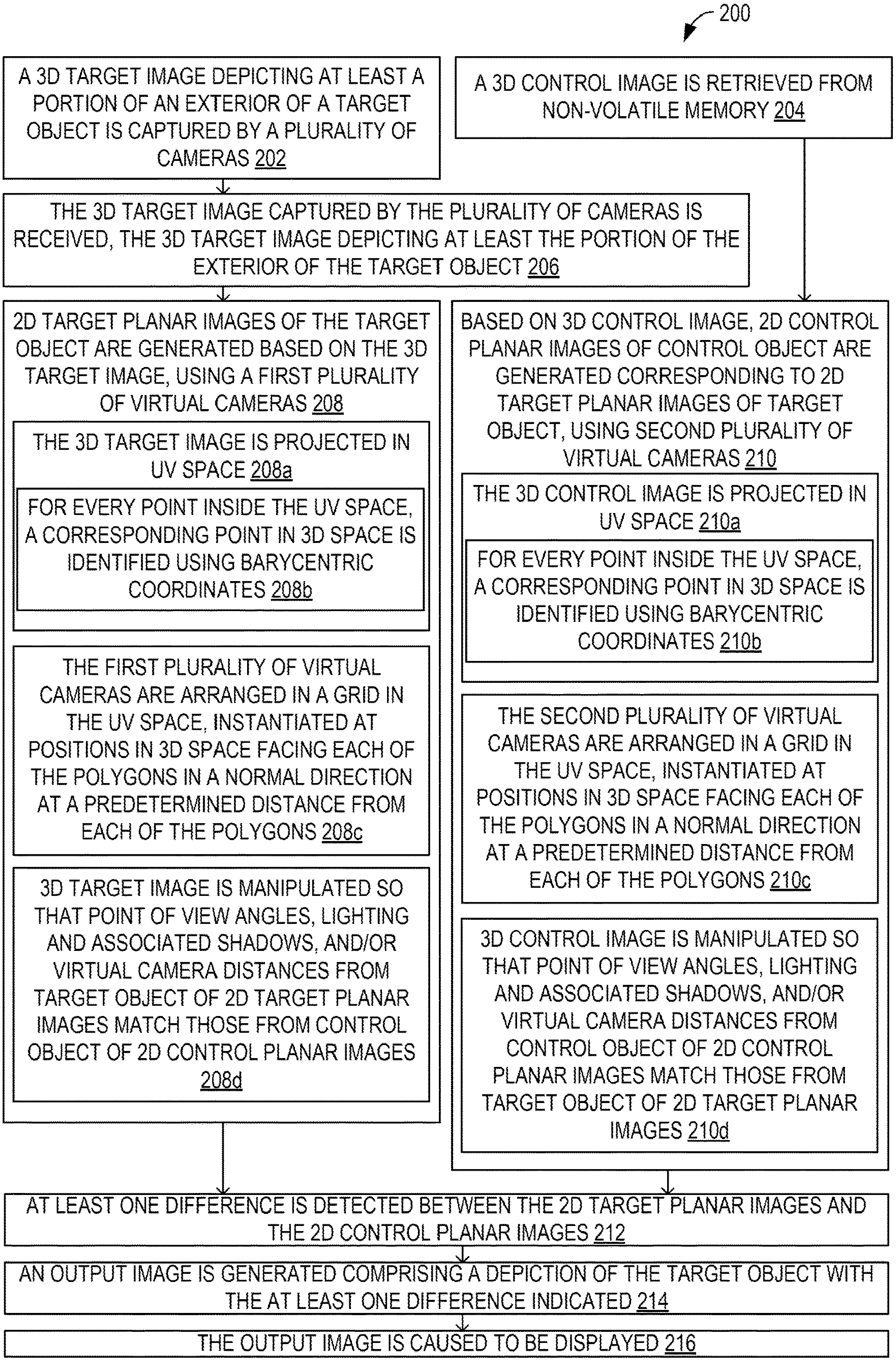
200
A 3D TARGET IMAGE DEPICTING AT LEAST A PORTION OF AN EXTERIOR OF A TARGET OBJECT IS CAPTURED BY A PLURALITY OF CAMERAS 202
A 3D CONTROL IMAGE IS RETRIEVED FROM NON-VOLATILE MEMORY 204
THE 3D TARGET IMAGE CAPTURED BY THE PLURALITY OF CAMERAS IS RECEIVED, THE 3D TARGET IMAGE DEPICTING AT LEAST THE PORTION OF THE EXTERIOR OF THE TARGET OBJECT 206
2D TARGET PLANAR IMAGES OF THE TARGET OBJECT ARE GENERATED BASED ON THE 3D TARGET IMAGE, USING A FIRST PLURALITY OF VIRTUAL CAMERAS 208
THE 3D TARGET IMAGE IS PROJECTED IN UV SPACE 208a
FOR EVERY POINT INSIDE THE UV SPACE, A CORRESPONDING POINT IN 3D SPACE IS IDENTIFIED USING BARYCENTRIC COORDINATES 208b
THE FIRST PLURALITY OF VIRTUAL CAMERAS ARE ARRANGED IN A GRID IN THE UV SPACE, INSTANTIATED AT POSITIONS IN 3D SPACE FACING EACH OF THE POLYGONS IN A NORMAL DIRECTION AT A PREDETERMINED DISTANCE FROM EACH OF THE POLYGONS 208c
3D TARGET IMAGE IS MANIPULATED SO THAT POINT OF VIEW ANGLES, LIGHTING AND ASSOCIATED SHADOWS, AND/OR VIRTUAL CAMERA DISTANCES FROM TARGET OBJECT OF 2D TARGET PLANAR IMAGES MATCH THOSE FROM CONTROL OBJECT OF 2D CONTROL PLANAR IMAGES 208d
BASED ON 3D CONTROL IMAGE, 2D CONTROL PLANAR IMAGES OF CONTROL OBJECT ARE GENERATED CORRESPONDING TO 2D TARGET PLANAR IMAGES OF TARGET OBJECT, USING SECOND PLURALITY OF VIRTUAL CAMERAS 210
THE 3D CONTROL IMAGE IS PROJECTED IN UV SPACE 210a
FOR EVERY POINT INSIDE THE UV SPACE, A CORRESPONDING POINT IN 3D SPACE IS IDENTIFIED USING BARYCENTRIC COORDINATES 210b
THE SECOND PLURALITY OF VIRTUAL CAMERAS ARE ARRANGED IN A GRID IN THE UV SPACE, INSTANTIATED AT POSITIONS IN 3D SPACE FACING EACH OF THE POLYGONS IN A NORMAL DIRECTION AT A PREDETERMINED DISTANCE FROM EACH OF THE POLYGONS 210c
3D CONTROL IMAGE IS MANIPULATED SO THAT POINT OF VIEW ANGLES, LIGHTING AND ASSOCIATED SHADOWS, AND/OR VIRTUAL CAMERA DISTANCES FROM CONTROL OBJECT OF 2D CONTROL PLANAR IMAGES MATCH THOSE FROM TARGET OBJECT OF 2D TARGET PLANAR IMAGES 210d
AT LEAST ONE DIFFERENCE IS DETECTED BETWEEN THE 2D TARGET PLANAR IMAGES AND THE 2D CONTROL PLANAR IMAGES 212
AN OUTPUT IMAGE IS GENERATED COMPRISING A DEPICTION OF THE TARGET OBJECT WITH THE AT LEAST ONE DIFFERENCE INDICATED 214
THE OUTPUT IMAGE IS CAUSED TO BE DISPLAYED 216

FIG. 8

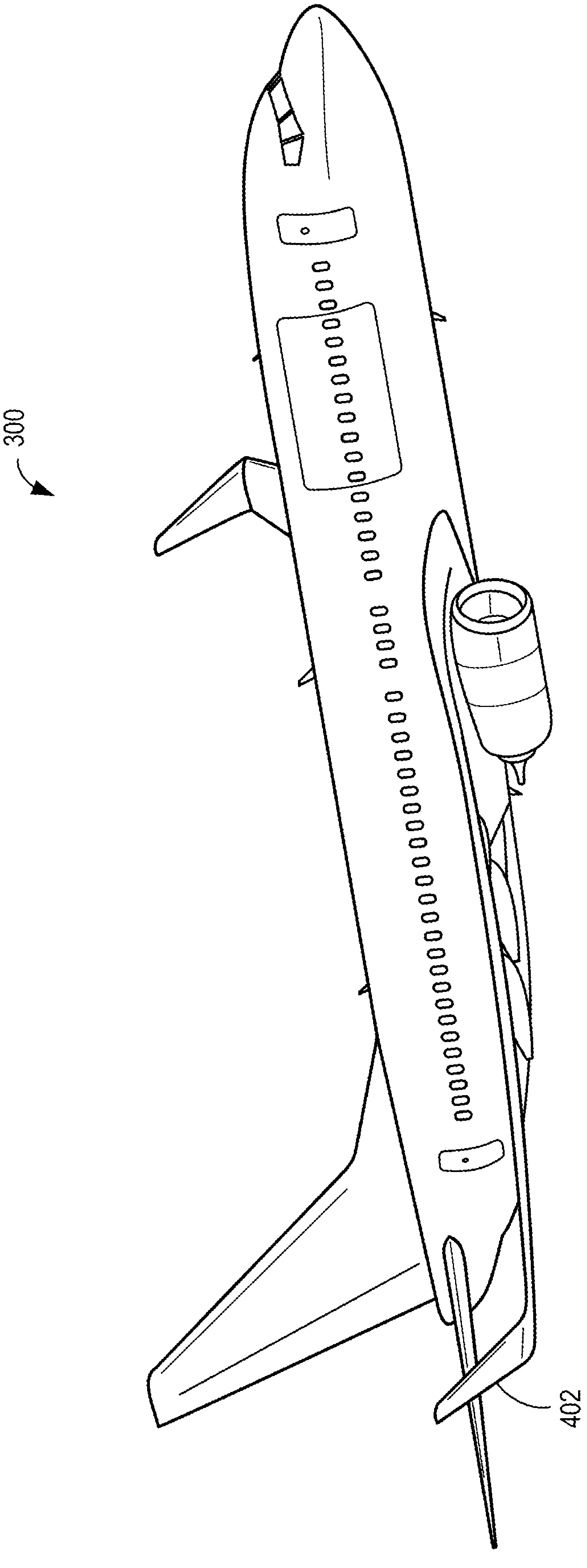

FIG. 9

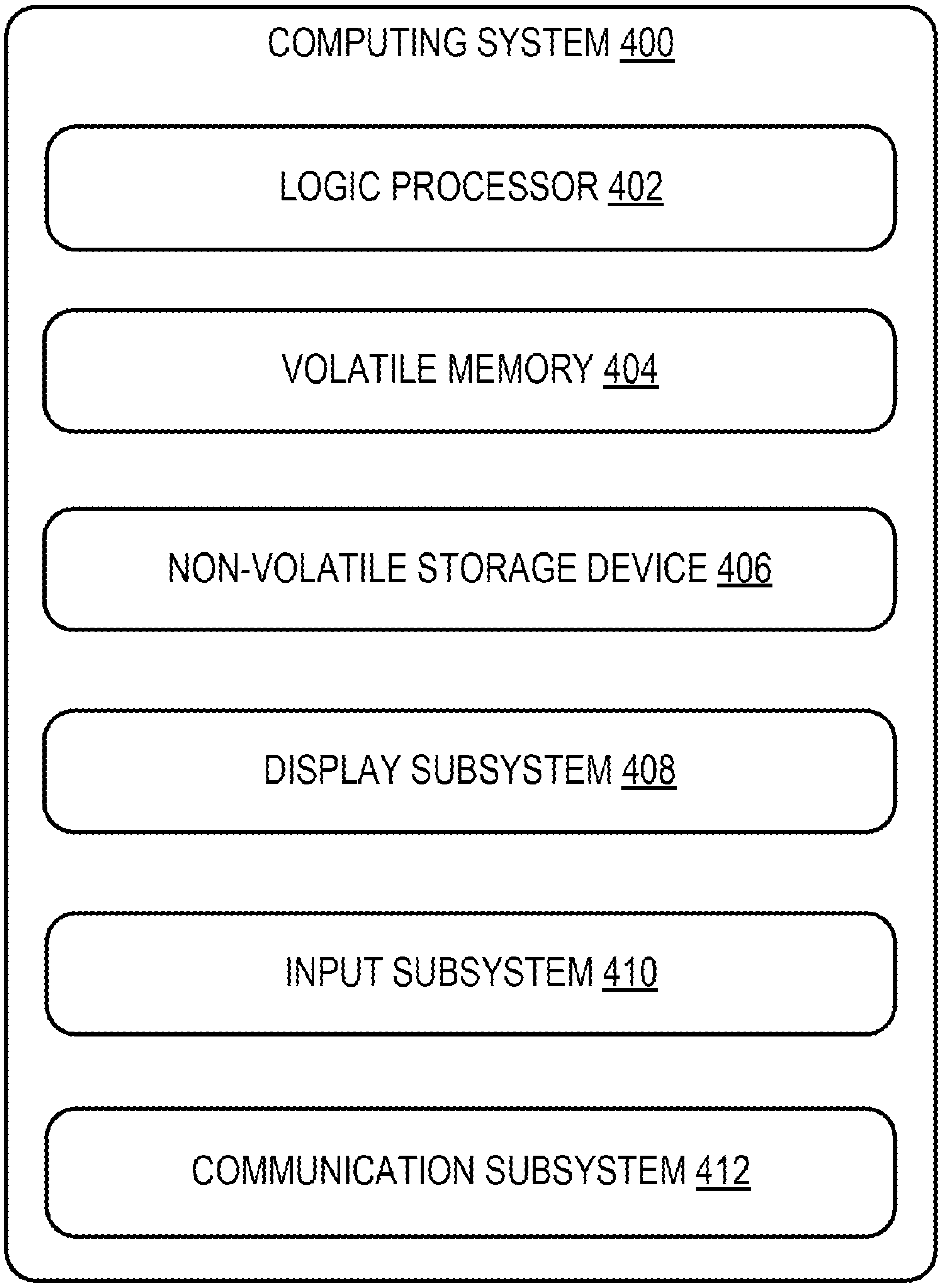
COMPUTING SYSTEM 400
LOGIC PROCESSOR 402
VOLATILE MEMORY 404
NON-VOLATILE STORAGE DEVICE 406
DISPLAY SUBSYSTEM 408
INPUT SUBSYSTEM 410
COMMUNICATION SUBSYSTEM 412

FIG. 10

SYSTEM AND METHOD FOR AUTOMATED SURFACE ANOMALY DETECTION

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application Ser. No. 63/159,387, filed Mar. 10, 2021, the entirety of which is hereby incorporated herein by reference for all purposes.

FIELD

The present disclosure relates generally to aircraft inspection and, in particular, to the inspection of the skin of manufactured or assembled parts of aircraft using three-dimensional modeling.

BACKGROUND

In aircraft manufacturing, inspection of the skin of manufactured or assembled parts is performed to find defects and anomalies. Existing visual inspection of the skin of the aircraft relies primarily on human visual acuity and can therefore be subjective. In addition, visual inspection can be swayed by human interpretation. The ability to promptly identify and address aircraft skin defects and anomalies can minimize potential delays due to rework. In addition, there is a need for a consistent quality inspection process that can be implemented not only at a manufacturer's facility but also at other sites, where there may be less expertise on potential issues and inspection criteria than at the manufacturer's site.

SUMMARY

In view of the above, a system for automated surface anomaly detection is provided, including at least one processor, communicatively coupled to non-volatile memory storing a 3D (three-dimensional) control image depicting at least a portion of an exterior of a control object and instructions that, when executed by the processor, cause the processor to: retrieve from the non-volatile memory the 3D control image; capture, by a plurality of cameras, a 3D target image depicting at least the portion of the exterior of a target object; receive the 3D target image captured by the plurality of cameras, the 3D target image depicting at least the portion of the exterior of the target object; generate 2D (two-dimensional) target planar images of the target object based on the 3D target image, using a first plurality of virtual cameras; generate 2D control planar images of the control object based on the 3D control image, the 2D control planar images corresponding to the 2D target planar images of the target object, using a second plurality of virtual cameras; detect at least one difference between the 2D target planar images and the 2D control planar images; generate an output image, wherein the output image comprises a depiction of the target object with the at least one difference indicated; and cause the output image to be displayed.

The features, functions, and advantages that have been discussed can be achieved independently in various embodiments or can be combined in yet other embodiments further details of which can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a general schematic diagram illustrating an overview of the system for automated surface anomaly detection, according to an embodiment of the subject disclosure.

FIG. **2** is a general schematic diagram illustrating an overview of inputs and outputs for the processor of the system for automated surface anomaly detection, according to an embodiment of the subject disclosure.

FIG. **3** is a general schematic diagram illustrating an overview of the system for automated surface anomaly detection including a server computing device, client computing device, and cameras connected to a network, according to an embodiment of the subject disclosure.

FIG. **4** is an illustration of the projection of a 3D image onto a UV map in the system for automated surface anomaly detection, according to an embodiment of the subject disclosure.

FIG. **5** is an illustration of a user interface for the image acquisition module of the system for automated surface anomaly detection, according to an embodiment of the subject disclosure.

FIG. **6** is an illustration of the instantiation of virtual cameras in a grid at positions in 3D space in the system for automated surface anomaly detection, according to an embodiment of the subject disclosure.

FIG. **7** is an illustration of the instantiation of virtual cameras at positions in 3D space in a normal direction at a predetermined distance from each of the polygons of a 3D image in the system for automated surface anomaly detection, according to an embodiment of the subject disclosure.

FIG. **8** is a flowchart of a method for automated surface anomaly detection, according to an embodiment of the subject disclosure.

FIG. **9** is an illustration of an aircraft that can be inspected by the system for automated surface anomaly detection, according to an embodiment of the subject disclosure.

FIG. **10** is a schematic diagram illustrating an exemplary computing system that can be used to implement the system for automated surface anomaly detection of FIGS. **1-3**.

DETAILED DESCRIPTION

In view of the above issues, as shown in FIGS. **1** and **2**, a system **10** for automated surface anomaly detection is provided, comprising at least one processor **14**, communicatively coupled to non-volatile memory **16** storing a 3D control image **30** depicting at least a portion of an exterior of a control object and instructions **32** that, when executed by the processor **14**, cause the processor **14** to retrieve the 3D control image **30** from the non-volatile memory **16**. The control object can be an aircraft or an aircraft component, for example. The processor **14** captures, by a plurality of cameras **26**, a 3D target image **34** depicting at least the portion of the exterior of a target object, which can be an aircraft or an aircraft component, for example. However, it will be appreciated that the control object and the target object are not particularly limited to aircraft and aircraft components, and the control object and the target object can be any manufactured part or component. The sizes of the control objects and the target objects are not particularly limited—the control object and the target object can be micron-scale objects in such applications as printed circuit boards or medical devices, or oversized objects that are too large for physical inspection using conventional segment-by-segment inspection methods under other 3D reconstruction-based visual inspection systems. The 3D control image **30** and the 3D target image **34** can comprise polygons rendered in a cross-platform 3D graphics format, which can allow the 3D images **30**, **34** to be accessed across multiple graphics platforms.

In this example, a first camera **26***a* and a second camera **26***b* are used to capture the 3D target image **34**. However, it will be appreciated that the quantity of cameras **26** is not particularly limited, and more than two cameras **26** can be used to capture the 3D target image **34**. The cameras **26** can include at least one depth camera, 3D scanner, visual sensors, RGB cameras, thermal cameras, LiDAR cameras, or a combination thereof. The non-volatile memory **16** can further store a UV map **50**, onto which the 3D control image **30** and the 3D target image **34** can be projected. The 3D target image **34** and the 3D control image **30** can be 3D point clouds of at least one of visual, thermal imaging, LiDAR, radar, or humidity sensors. The 3D control image **30** serves as a reference image for purposes of automated image comparison to the 3D target image **34**.

The processor **14** receives the 3D target image **34** captured by the plurality of cameras **26**, the 3D target image **34** depicting at least the portion of the exterior of the target object. Using a first plurality of virtual cameras **36**, the processor **14** generates 2D target planar images **38** of the target object based on the 3D target image **34**. Using a second plurality of virtual cameras **40**, the processor **14** generates 2D control planar images **42** of the control object based on the 3D control image **30**, the 2D control planar images **42** corresponding to the 2D target planar images **38** of the target object, so that the poses and locations in the 2D target planar images **38** correspond to those in the 2D control planar images **42**. The first plurality of virtual cameras **36** and the second plurality of virtual cameras **40** can take the 2D target planar images **38** and the 2D control planar images **42** as perpendicularly as possible to the surface of the 3D target image **34** and the 3D control image **30**, respectively. Images can be taken along an entire surface and an entire curvature of the 3D target image **34** so that as many anomalies can be detected as possible. Surface anomalies can include dents, holes, scratches, tears, chips, cracks, peels, burns, delaminations, melted metal, and missing sealant, for example.

The processor **14** can be configured so that an image acquisition module **52** of the processor **14** receives, as input, the 3D control image **30**, the UV map **50**, and the 3D target image **34**, generates the 2D target planar images **38** and the 2D control planar images **42**, and outputs the 2D target planar images **38** and the 2D control planar images **42**.

The processor **14** generates 2D image pairs **44** pairing the 2D control planar images **42** to the 2D target planar images **38**. Comparing the 2D target planar images **38** to the 2D control planar images **42**, the 2D image pairs **44** taken of the parts for both the target object and the control object are compared side-by-side. It will be appreciated that comparing the control object and the target object side-by-side and in the same graphical representation eliminates format conflicts and mismatches between 3D graphical systems and models. For each 2D image pair **44**, the 2D control planar image **42** and the 2D target planar image **38** are taken in the same pose and at the same location. The processor **14** detects at least one difference **46** or anomaly between the 2D target planar images **38** and the 2D control planar images **42**, identifying the coordinates of the identified difference **46** in both 3D space and the UV space in the UV map **50**. The processor **14** then generate an output image **48** comprising a depiction of the target object with the at least one difference **46** indicated or annotated, and causes the output image **48** to be displayed on a display **28**. The 2D image pair **44** and detected differences **46**, including the coordinates of the identified differences **46** in both 3D space and the UV space in the UV map **50**, can be stored in non-volatile memory **16** for later use in various applications, including the training of deep learning models for automatically classifying types of anomalies. A large body of images showing a target defect can be used to train a deep learning model to automatically classify the target defect. For example, thousands of image pairs showing an inward dent can be used to train a deep learning model to automatically classify the inward dent.

The processor **14** can be configured so that an image comparison module **54** of the processor **14** receives, as input, the 2D target planar images **38** and the 2D control planar images **42** as 2D image pairs **44**, compares the 2D image pairs **44** taken of the parts for both the target object and the control object side-by-side, detects at least one difference **46** between the 2D target planar images **38** and the 2D control planar images **42**, generates an output image **48** comprising a depiction of the target object with the at least one difference **46** indicated or annotated, and outputs the output image **48**. The image comparison module **54** can accept image comparison segmentation parameters **56** for controlling how the difference **46** is indicated or annotated on the 2D image pairs **44**. In this example, the difference **46** is indicated or annotated by a circle.

FIG. **3** is a schematic diagram of the system **10** for automated anomaly detection comprising a server computing device **12** which includes one or more processors **14**, which can be communicatively coupled to a network **22**. The server computing device **12** includes a network interface **18** to affect the communicative coupling to the network **22**, and, through the network **22**, a client computing device **24** and a plurality of cameras **26**. The client computing device **24** comprises a display **28** which is configured to display an output image **48**. Network interface **18** can include a physical network interface, such as a network adapter. The server computing device **12** can be a special-purpose computer, adapted for reliability and high-bandwidth communications. Thus, the system **10** can be embodied in a cluster of individual hardware server computers, for example. The processor **14** can be multi-core processors suitable for handling large amounts of information. The processor **14** is communicatively coupled to non-volatile memory **16** storing a 3D control image **30**, UV map **50**, and instructions **32**, which can be executed by the processor **14** to effectuate the techniques disclosed herein on concert with the client computing device **24** as shown and described below. The non-volatile memory **16** can be in a Redundant Array of Inexpensive Disk drives (RAID) configuration for added reliability. The processor **14** can also be communicatively coupled to graphical co-processors (GPU) **20**. Graphical co-processors can expedite the technique disclosed herein by performing operations in parallel.

Referring to FIG. **4**, the projection of the 3D image (3D control image **30** or 3D target image **34**) onto a UV map **50** is depicted. For every point inside the mesh in the UV map **50**, a corresponding point is found by the processor in the 3D space **58** using Barycentric coordinates. A UV coordinate is determined and stored for each vertex in a mesh of the 3D image, so that the contours, vertices, faces, and edges of the 3D image in the 3D space **58** correspond to those in the UV map **50**. Accordingly, the processor projects the 3D control image **30** and the 3D target image **34** in UV space of the UV map **50**. Further, when an anomaly or difference is detected in the 3D target image **34**, the location of the difference can be identified in the coordinates of both the 3D space **58** and the UV map **50**, thereby eliminating expensive localization and mapping processing.

Referring to FIG. **5**, a user interface **60** for the image acquisition module is illustrated. The user interface **60** includes a first field **62** to select a U-resolution, a second field **64** to select a V-resolution, a third field **66** to select a grid spacing for the virtual U-cameras, a fourth field **68** to select a grid spacing for the virtual V-cameras, and a fifth field **70** to select a camera standoff distance from the surface of the polygons of the 3D images. A check box **72** can be provided to toggle the display of camera positions. A first browse button **74** can be provided to select a 3D target object, and a second browse button **76** can be provided to select a 3D control object. An image capture window **78** can display the 3D target object and the 3D control object. Upon clicking the OK button **80**, the image acquisition module can proceed to receive the 3D target object and the 3D control object, instantiate the virtual cameras in accordance with the properties entered in the first field **62**, second field **64**, third field **66**, fourth field **68**, and fifth field **70**, and generate the 2D target planer images and 2D planar images accordingly.

Referring to FIG. **6**, the arrangement of the first plurality of virtual cameras **36** or second plurality of virtual cameras **40** in a grid in the UV map **50** is depicted. A grid of potential camera positions is generated in UV map **50**. The grid spacing for the virtual U-cameras is configured in accordance with the selection in the third field **66** in the user interface **60**, and the grid spacing for the virtual V-cameras is configured in accordance with the selection in the fourth field **68** in the user interface **60**. Then, the camera positions outside of the projected mesh in the UV map are ignored. The ignored camera positions are depicted as white circles in the depiction of FIG. **6**. Accordingly, the processor arranges the first plurality of virtual cameras **36** and the second plurality of virtual cameras **40** in a grid in the UV space of the UV map **50**. In some embodiments, the processor can determine the optimal grid spacing for the virtual U-cameras and the virtual V-cameras that allow the virtual cameras to face the polygons of the 3D image in a perpendicular orientation, or an orientation within a predetermined deviation from perpendicular orientation to the surface of the polygons.

Referring to FIG. **7**, the instantiation of virtual cameras **36**, **40** is depicted at positions in 3D space **58** facing each of the polygons of the 3D image **30**, **34** in a normal direction at a predetermined distance **82** from each of the polygons. The camera standoff distance **82** from the surface of the polygons of the 3D images is configured in accordance with the fifth field **70** of the user interface **60**. The 3D target image **34** and the 3D control image **30** are manipulated by the processor so that point of view angles, lighting and associated shadows, and/or virtual camera distances from target object of 2D target planar images match those from control object of 2D control planar images. Accordingly, lighting condition biases are removed, and 2D planar images are taken by the virtual cameras **36**, **40** that face the polygons of the 3D image **30**, **34** in a perpendicular orientation, or an orientation within a predetermined deviation from perpendicular orientation to the surface of the polygons. The predetermined deviation can be 5% to 10% from perpendicular orientation, for example.

FIG. **8** shows an exemplary method **200** for automated anomaly detection according to an example of the present disclosure. The following description of method **200** is provided with reference to the software and hardware components described above and shown in FIGS. **1** through **3**. It will be appreciated that method **200** also can be performed in other contexts using other suitable hardware and software components.

At step **202**, a 3D target image depicting at least a portion of an exterior of a target object is captured by a plurality of cameras, which can be a 3D scanner or at least one depth camera. At step **204**, a 3D control image, which can comprise polygons, is retrieved from non-volatile memory. At step **206**, the 3D target image captured by the plurality of cameras is received, the 3D target image depicting at least the portion of the exterior of the target object. The 3D target image can comprise polygons. The target object and the control object can be aircraft or aircraft components.

At step **208**, 2D target planar images of the target object are generated based on the 3D target image, using a first plurality of virtual cameras. Step **208** can include step **208***a*, at which the 3D target image is projected in UV space. Step **208***a* can include step **208***b*, in which for every point inside the UV space, a corresponding point in 3D space is identified using Barycentric coordinates. Step **208** can further include step **208***c*, in which the first plurality of virtual cameras are arranged in a grid in the UV space, instantiated at positions in 3D space facing each of the polygons in a normal direction at a predetermined distance from each of the polygons. Step **208** can further include step **208***d*, in which the 3D target image is manipulated so that point of view angles, lighting and associated shadows, and/or virtual camera distances from target object of 2D target planar images match those from control object of 2D control planar images. Accordingly, lighting condition biases are removed.

At step **210**, based on 3D control image, 2D control planar images of control object are generated corresponding to 2D target planar images of target object, using second plurality of virtual cameras. Step **210** can include step **210***a*, in which the 3D control image is projected in UV space. Step **210***a* can include step **210***b*, in which for every point inside the UV space, a corresponding point in 3D space is identified using Barycentric coordinates. Step **210** can further include step **210***c*, in which the second plurality of virtual cameras are arranged in a grid in the UV space, instantiated at positions in 3D space facing each of the polygons in a normal direction at a predetermined distance from each of the polygons. Step **210** can further include step **210***d*, in which the 3D control image is manipulated so that point of view angles, lighting and associated shadows, and/or virtual camera distances from control object of 2D control planar images match those from target object of 2D target planar images.

At step **212**, at least one difference is detected between the 2D target planar images and the 2D control planar images. At step **214**, an output image is generated comprising a depiction of the target object with the at least one difference indicated or annotated. At step **216**, the output image is caused to be displayed.

FIG. **9** is an image of an aircraft **300** according to some embodiments. It will be appreciated that the aircraft **300** or the components thereof can be the target object or the control object of the 3D target image or the 3D control image, respectively, that are inspected in accordance with the system **10** and method **200** of the subject disclosure.

The systems and processes described herein have the potential benefit of replacing subjective visual inspections based on human visual acuity and swayed by human interpretation with objective, computer-aided inspections based on unbiased evaluation of image data. This enables the inspection of the surfaces of manufactured parts in a simulated virtual and automated environment, in which lighting conditions can be controlled to be uniform. In other words, uniform light intensity and light angle can be achieved with light condition biases eliminated. Thus, thorough coverage of the surfaces of any manufactured part or component, including micro-scale and oversized parts and components, can be achieved without inadvertently missing any areas due to poor lighting conditions. Accordingly, expensive image capture apparatuses with rails or other support structures, multitudes of movable and static high definition cameras, and sensors to detect reflections, shadows, and other transient visual phenomena can be dispensed with to reduce costs and increase efficiencies in aircraft inspection. Indeed, unlike physical cameras, there is no physical limitation on the types and numbers of virtual cameras that can be applied to capture 2D planar images. Furthermore, expensive localization and mapping processing is eliminated by identifying the coordinates of identified anomalies in both 3D space and the UV space in the UV map. Having both the control object and the target object side-by-side and in the same graphical representation eliminates format conflicts and mismatches between different 3D graphical systems and models. Since modifications on the control object has the exact same effect on the target object, statistical quality control can be achieved, especially for the design of experiments where control variables are needed to identify significant factors on the quality and behavior of external surfaces.

FIG. **10** illustrates an exemplary computing system **400** that can be utilized to implement the system **10** and method **200** described above. Computing system **400** includes a logic processor **402**, volatile memory **404**, and a non-volatile storage device **406**. Computing system **400** can optionally include a display subsystem **408**, input subsystem **410**, communication subsystem **412** connected to a computer network, and/or other components not shown in FIG. **9**. These components are typically connected for data exchange by one or more data buses when integrated into single device, or by a combination of data buses, network data interfaces, and computer networks when integrated into separate devices connected by computer networks.

The non-volatile storage device **406** stores various instructions, also referred to as software, that are executed by the logic processor **402**. Logic processor **402** includes one or more physical devices configured to execute the instructions. For example, the logic processor **402** can be configured to execute instructions that are part of one or more applications, programs, routines, libraries, objects, components, data structures, or other logical constructs. Such instructions can be implemented to perform a task, implement a data type, transform the state of one or more components, achieve a technical effect, or otherwise arrive at a desired result.

The logic processor **402** can include one or more physical processors (hardware) configured to execute software instructions. Additionally or alternatively, the logic processor **402** can include one or more hardware logic circuits or firmware devices configured to execute hardware-implemented logic or firmware instructions. Processors of the logic processor **402** can be single-core or multi-core, and the instructions executed thereon can be configured for sequential, parallel, and/or distributed processing. Individual components of the logic processor **402** optionally can be distributed among two or more separate devices, which can be remotely located and/or configured for coordinated processing. Aspects of the logic processor **402** can be virtualized and executed by remotely accessible, networked computing devices configured in a cloud-computing configuration. In such a case, these virtualized aspects are run on different physical logic processors of various different machines, it will be understood.

Non-volatile storage device **406** includes one or more physical devices configured to hold instructions executable by the logic processors to implement the methods and processes described herein. When such methods and processes are implemented, the state of non-volatile storage device **406** can be transformed—e.g., to hold different data.

Non-volatile storage device **406** can include physical devices that are removable and/or built-in. Non-volatile storage device **406** can include optical memory (e.g., CD, DVD, HD-DVD, Blu-Ray Disc, etc.), semiconductor memory (e.g., ROM, EPROM, EEPROM, FLASH memory, etc.), and/or magnetic memory (e.g., hard-disk drive, floppy-disk drive, tape drive, MRAM, etc.), or other mass storage device technology. Non-volatile storage device **406** can include nonvolatile, dynamic, static, read/write, read-only, sequential-access, location-addressable, file-addressable, and/or content-addressable devices. It will be appreciated that non-volatile storage device **406** is configured to hold instructions even when power is cut to the non-volatile storage device **406**.

Volatile memory **404** can include physical devices that include random access memory. Volatile memory **404** is typically utilized by logic processor **402** to temporarily store information during processing of software instructions. It will be appreciated that volatile memory **404** typically does not continue to store instructions when power is cut to the volatile memory **404**.

Aspects of logic processor **402**, volatile memory **404**, and non-volatile storage device **406** can be integrated together into one or more hardware-logic components. Such hardware-logic components can include field-programmable gate arrays (FPGAs), program- and application-specific integrated circuits (PASIC/ASICs), program- and application-specific standard products (PSSP/ASSPs), system-on-a-chip (SOC), and complex programmable logic devices (CPLDs), for example.

The terms "module," "program," and "engine" can be used to describe an aspect of the security computing system **10** typically implemented in software by a processor to perform a particular function using portions of volatile memory, which function involves transformative processing that specially configures the processor to perform the function. Thus, a module, program, or engine can be instantiated via logic processor **402** executing instructions held by non-volatile storage device **406**, using portions of volatile memory **404**. It will be understood that different modules, programs, and/or engines can be instantiated from the same application, service, code block, object, library, routine, API, function, etc. Likewise, the same module, program, and/or engine can be instantiated by different applications, services, code blocks, objects, routines, APIs, functions, etc. The terms "module," "program," and "engine" can encompass individual or groups of executable files, data files, libraries, drivers, scripts, database records, etc.

Display subsystem **408** typically includes one or more displays, which can be physically integrated with or remote from a device that houses the logic processor **402**. Graphical output of the logic processor executing the instructions described above, such as a graphical user interface, is configured to be displayed on display subsystem **408**.

Input subsystem **410** typically includes one or more of a keyboard, pointing device (e.g., mouse, trackpad, finger operated pointer), touchscreen, microphone, and camera. Other input devices can also be provided.

Communication subsystem **412** is configured to communicatively couple various computing devices described herein with each other, and with other devices. Communication subsystem **412** can include wired and/or wireless communication devices compatible with one or more different communication protocols. As non-limiting examples, the communication subsystem can be configured for communication via a wireless telephone network, or a wired or wireless local- or wide-area network by devices such as a 3G, 4G, 5G, or 6G radio, WIFI card, ethernet network interface card, BLUETOOTH® radio, etc. In some embodiments, the communication subsystem can allow computing system **10** to send and/or receive messages to and/or from other devices via a network such as the Internet. It will be appreciated that one or more of the computer networks via which communication subsystem **412** is configured to communicate can include security measures such as user identification and authentication, access control, malware detection, enforced encryption, content filtering, etc., and can be coupled to a wide area network (WAN) such as the Internet.

The subject disclosure includes all novel and non-obvious combinations and subcombinations of the various features and techniques disclosed herein. The various features and techniques disclosed herein are not necessarily required of all examples of the subject disclosure. Furthermore, the various features and techniques disclosed herein can define patentable subject matter apart from the disclosed examples and can find utility in other implementations not expressly disclosed herein.

To the extent that terms "includes," "including," "has," "contains," and variants thereof are used herein, such terms are intended to be inclusive in a manner similar to the term "comprises" as an open transition word without precluding any additional or other elements.

It will be appreciated that "and/or" as used herein refers to the logical disjunction operation, and thus A and/or B has the following truth table.

A	B	A and/or B
T	T	T
T	F	T
F	T	T
F	F	F

To the extent that terms "includes," "including," "has," "contains," and variants thereof are used herein, such terms are intended to be inclusive in a manner similar to the term "comprises" as an open transition word without precluding any additional or other elements.

Further, the disclosure comprises configurations according to the following clauses.

Clause 1. A system for automated surface anomaly detection, the system comprising: at least one processor, communicatively coupled to non-volatile memory storing a 3D control image depicting at least a portion of an exterior of a control object and instructions that, when executed by the processor, cause the processor to: retrieve from the non-volatile memory the 3D control image; capture, by a plurality of cameras, a 3D target image depicting at least the portion of the exterior of a target object; receive the 3D target image captured by the plurality of cameras, the 3D target image depicting at least the portion of the exterior of the target object; generate 2D target planar images of the target object based on the 3D target image, using a first plurality of virtual cameras; generate 2D control planar images of the control object based on the 3D control image, the 2D control planar images corresponding to the 2D target planar images of the target object, using a second plurality of virtual cameras; detect at least one difference between the 2D target planar images and the 2D control planar images; generate an output image, wherein the output image comprises a depiction of the target object with the at least one difference indicated; and cause the output image to be displayed.

Clause 2. The system of clause 1, wherein, to generate the 2D target planar images of the target object and the 2D control planar images of the control object, the processor manipulates the 3D target image and/or the 3D target image so that point of view angles, lighting and associated shadows, and/or virtual camera distances from the target object of the 2D target planar images match point of view angles, lighting and associated shadows, and/or virtual camera distances from the control object of the 2D control planar images.

Clause 3. The system of clause 1 or 2, wherein the processor projects the 3D control image and the 3D target image in UV space.

Clause 4. The system of clause 3, wherein the processor arranges the first plurality of virtual cameras and the second plurality of virtual cameras in a grid in the UV space.

Clause 5. The system of clause 3 or 4, wherein, for every point inside the UV space, the processor identifies a corresponding point in 3D space using Barycentric coordinates.

Clause 6. The system of any of clauses 1 to 5, wherein the 3D control image and the 3D target image comprise polygons.

Clause 7. The system of clause 6, wherein the virtual cameras are instantiated at positions in 3D space facing each of the polygons in a normal direction at a predetermined distance from each of the polygons.

Clause 8. The system of any of clauses 1 to 7, wherein the target object and the control object are aircraft or aircraft components.

Clause 9. The system of any of clauses 1 to 8, wherein the at least one difference, the 2D target planar images, and the 2D control planar images are stored in the non-volatile memory and subsequently used to train a deep learning module to classify the difference.

Clause 10. A method for automated surface anomaly detection, the method comprising: retrieving from non-volatile memory a 3D control image; capturing, by a plurality of cameras, a 3D target image depicting at least a portion of an exterior of a target object; receiving the 3D target image captured by the plurality of cameras, the 3D target image depicting at least the portion of the exterior of the target object; generating 2D target planar images of the target object based on the 3D target image, using a first plurality of virtual cameras; generating 2D control planar images of a control object based on the 3D control image, the 2D control planar images corresponding to the 2D target planar images of the target object, using a second plurality of virtual cameras; detecting at least one difference between the 2D target planar images and the 2D control planar images; generating an output image, wherein the output image comprises a depiction of the target object with the at least one difference indicated; and causing the output image to be displayed.

Clause 11. The method of clause 10, wherein, to generate the 2D target planar images of the target object and the 2D control planar images of the control object, the 3D target image and/or the 3D target image is manipulated so that point of view angles, lighting and associated shadows, and/or virtual camera distances from the target object of the 2D target planar images match point of view angles, lighting and associated shadows, and/or virtual camera distances from the control object of the 2D control planar images.

Clause 12. The method of clause 10 or 11, wherein the 3D control image and the 3D target image are projected in UV space.

Clause 13. The method of any of clauses 10 to 12, wherein the first plurality of virtual cameras and the second plurality of virtual cameras are arranged in a grid in the UV space.

Clause 14. The method of any of clauses 10 to 13, wherein, for every point inside the UV space, a corresponding point in 3D space is identified using Barycentric coordinates.

Clause 15. The method of any of clauses 10 to 14, wherein the 3D control image and the 3D target image comprise polygons.

Clause 16. The method of clause 15, wherein the virtual cameras are instantiated at positions in 3D space facing each of the polygons in a normal direction at a predetermined distance from each of the polygons.

Clause 17. The method of any of clauses 10 to 16, wherein the target object and the control object are aircraft or aircraft components.

Clause 18. The method of any of clauses 10 to 17, wherein the at least one difference, the 2D target planar images, and the 2D control planar images are stored in the non-volatile memory and subsequently used to train a deep learning module to classify the difference.

Clause 19. A system for automated surface anomaly detection, the system comprising: non-volatile memory storing instructions and a 3D control image depicting at least a portion of an exterior of a control aircraft; a plurality of cameras disposed to capture a 3D target image of a portion of an exterior of a target aircraft corresponding to the portion of the exterior of the target aircraft; and at least one electronic processor, communicatively coupled to the non-volatile memory and the plurality of cameras, that executes the instructions to cause the processor to: retrieve from the non-volatile memory the 3D control image; capture, by the plurality of cameras, the 3D target image depicting at least the portion of the exterior of the target aircraft; receive the 3D target image captured by the plurality of cameras, the 3D target image depicting at least the portion of the exterior of the target aircraft; project the 3D control image and the 3D target image in UV space; identify a corresponding point in 3D space using Barycentric coordinates for every point inside the UV space; generate 2D target planar images of the target aircraft based on the 3D target image, using a first plurality of virtual cameras arranged in a grid in the UV space; generate 2D control planar images of the control aircraft based on the 3D control image, the 2D control planar images corresponding to the 2D target planar images of the target aircraft, using a second plurality of virtual cameras arranged in the grid in the UV space, the first plurality of virtual cameras and the second plurality of virtual cameras instantiated at identical positions in the 3D space; detect at least one anomaly between the 2D target planar images and the 2D control planar images; generate an output image, wherein the output image comprises a depiction of the target aircraft with the at least one anomaly annotated; and cause the output image to be displayed.

Clause 20. The system of clause 19, wherein the 3D target image and the 3D control image are 3D point clouds of at least one of thermal imaging, LiDAR, radar, or humidity sensors.

The invention claimed is:

1. A system for automated surface anomaly detection, the system comprising:

at least one processor, communicatively coupled to non-volatile memory storing a 3D control image depicting at least a portion of an exterior of a control object and instructions that, when executed by the processor, cause the processor to:

retrieve from the non-volatile memory the 3D control image;

capture, by a plurality of cameras, a 3D target image depicting at least the portion of the exterior of a target object;

receive the 3D target image captured by the plurality of cameras, the 3D target image depicting at least the portion of the exterior of the target object;

generate 2D target planar images of the target object based on the 3D target image, using a first plurality of virtual cameras;

generate 2D control planar images of the control object based on the 3D control image, the 2D control planar images corresponding to the 2D target planar images of the target object, using a second plurality of virtual cameras;

detect at least one difference between the 2D target planar images and the 2D control planar images;

generate an output image, wherein the output image comprises a depiction of the target object with the at least one difference indicated; and

cause the output image to be displayed.

2. The system of claim 1, wherein, to generate the 2D target planar images of the target object and the 2D control planar images of the control object, the processor manipulates the 3D target image and/or the 3D control image so that point of view angles, lighting and associated shadows, and/or virtual camera distances from the target object of the 2D target planar images match point of view angles, lighting and associated shadows, and/or virtual camera distances from the control object of the 2D control planar images.

3. The system of claim 1, wherein the processor projects the 3D control image and the 3D target image in UV space.

4. The system of claim 3, wherein the processor arranges the first plurality of virtual cameras and the second plurality of virtual cameras in a grid in the UV space.

5. The system of claim 3, wherein, for every point inside the UV space, the processor identifies a corresponding point in 3D space using Barycentric coordinates.

6. The system of claim 1, wherein the 3D control image and the 3D target image comprise polygons.

7. The system of claim 6, wherein the virtual cameras are instantiated at positions in 3D space facing each of the polygons in a normal direction at a predetermined distance from each of the polygons.

8. The system of claim 1, wherein the target object and the control object are aircraft or aircraft components.

9. The system of claim 1, wherein the at least one difference, the 2D target planar images, and the 2D control planar images are stored in the non-volatile memory and subsequently used to train a deep learning module to classify the difference.

10. A method for automated surface anomaly detection, the method comprising:

retrieving from non-volatile memory a 3D control image;

capturing, by a plurality of cameras, a 3D target image depicting at least a portion of an exterior of a target object;

receiving the 3D target image captured by the plurality of cameras, the 3D target image depicting at least the portion of the exterior of the target object;

generating 2D target planar images of the target object based on the 3D target image, using a first plurality of virtual cameras;

generating 2D control planar images of a control object based on the 3D control image, the 2D control planar images corresponding to the 2D target planar images of the target object, using a second plurality of virtual cameras;

detecting at least one difference between the 2D target planar images and the 2D control planar images;

generating an output image, wherein the output image comprises a depiction of the target object with the at least one difference indicated; and

causing the output image to be displayed.

11. The method of claim **10**, wherein, to generate the 2D target planar images of the target object and the 2D control planar images of the control object, the 3D target image and/or the 3D control image is manipulated so that point of view angles, lighting and associated shadows, and/or virtual camera distances from the target object of the 2D target planar images match point of view angles, lighting and associated shadows, and/or virtual camera distances from the control object of the 2D control planar images.

12. The method of claim **10**, wherein the 3D control image and the 3D target image are projected in UV space.

13. The method of claim **12**, wherein the first plurality of virtual cameras and the second plurality of virtual cameras are arranged in a grid in the UV space.

14. The method of claim **10**, wherein, for every point inside the UV space, a corresponding point in 3D space is identified using Barycentric coordinates.

15. The method of claim **10**, wherein the 3D control image and the 3D target image comprise polygons.

16. The method of claim **15**, wherein the virtual cameras are instantiated at positions in 3D space facing each of the polygons in a normal direction at a predetermined distance from each of the polygons.

17. The method of claim **10**, wherein the target object and the control object are aircraft or aircraft components.

18. The method of claim **10**, wherein the at least one difference, the 2D target planar images, and the 2D control planar images are stored in the non-volatile memory and subsequently used to train a deep learning module to classify the difference.

19. A system for automated surface anomaly detection, the system comprising:

non-volatile memory storing instructions and a 3D control image depicting at least a portion of an exterior of a control aircraft;

a plurality of cameras disposed to capture a 3D target image of a portion of an exterior of a target aircraft corresponding to the portion of the exterior of the target aircraft; and

at least one electronic processor, communicatively coupled to the non-volatile memory and the plurality of cameras, that executes the instructions to cause the processor to:

retrieve from the non-volatile memory the 3D control image;

capture, by the plurality of cameras, the 3D target image depicting at least the portion of the exterior of the target aircraft;

receive the 3D target image captured by the plurality of cameras, the 3D target image depicting at least the portion of the exterior of the target aircraft;

project the 3D control image and the 3D target image in UV space;

identify a corresponding point in 3D space using Barycentric coordinates for every point inside the UV space;

generate 2D target planar images of the target aircraft based on the 3D target image, using a first plurality of virtual cameras arranged in a grid in the UV space;

generate 2D control planar images of the control aircraft based on the 3D control image, the 2D control planar images corresponding to the 2D target planar images of the target aircraft, using a second plurality of virtual cameras arranged in the grid in the UV space, the first plurality of virtual cameras and the second plurality of virtual cameras instantiated at identical positions in the 3D space;

detect at least one anomaly between the 2D target planar images and the 2D control planar images;

generate an output image, wherein the output image comprises a depiction of the target aircraft with the at least one anomaly annotated; and

cause the output image to be displayed.

20. The system of claim **19**, wherein the 3D target image and the 3D control image are 3D point clouds of at least one of thermal imaging, LiDAR, radar, or humidity sensors.

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